Lightweight Innovations for Tomorrow (LIFT): Fuel saving potentials for heavy-duty vehicles, trains, ships, and aircraft

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LIFT Mission

• Accelerate the development and application of innovative lightweight metal production and component manufacturing technologies to benefit the US transportation, aerospace and defense market sectors.

• LIFT brings together > 100-member organizations that pair the world’s leading aluminum, titanium, magnesium and high strength steel manufacturers with universities and labs pioneering new applied technology development and research to deliver high value advanced alloy processing technologies that reduce the weight of machines that move people and goods on land, sea and air.

https://lift.technology/
LIFT LCA Crosscut

**Organization**

**Pillars**
- Melt processing
- Powder processing
- Thermo-mechanical processing
- Agile processing
- Coatings
- Joining and Assembly

**Projects (e.g.)**
- Thin-wall ductile cast iron
- Thin-wall aluminum die castings (upcoming)

**Crosscut**
- ICME
- Design
- LCA
- Validation/Certification
- Cost modeling
- Supply chain
- Corrosion
- Ballistic/Blast
LIFT technology portfolio

Increasing value of weight reduction & decreasing units/year

- $200 / pound saved (~$450/kg)
- $2 / pound saved (~$4.50/kg)
Fuel Saving Potentials

- OEM pathways to reduce use phase fuel consumption (FC) across modes in the US
  - Advanced and more efficient powertrains
  - Vehicle mass ($M_{vh}$) reduction – our focus here

- Key fuel use metrics across transportation modes:
  - FC and Fuel Intensity ($FI = FC/M_{cargo}$)
  - Both are dependent on Fuel Reduction Value ($FRV = \Delta FC/\Delta M$)

- LW Manufacturing Technologies enable a $\Delta M_{vh}$
  - Part and component LW
  - Shipping container LW across modes

- $\Delta M_{vh}$ also impacts other phases of vehicle life cycles
Table 2.8 in S.C. Davis, S.W. Diegel, and R.G. Bundy, 2016. Transportation Energy Data Book: Edition 35. Oak Ridge National Laboratory, Oak Ridge, TN.
FC Vehicle Mass Dependency across modes

Mass Component of US Fuel Consumption

Reduction Opportunity:
Vehicle Mass/Gross Vehicle Mass

- LW opportunity for OEMs is with vehicle mass
  - Ratio of $M_{vh}/M_{gv}$

$M_{vh} = \text{vehicle mass}$

$M_{cargo} = \text{cargo mass}$

$M_{gv} = \text{gross vehicle mass} = M_{vh} + M_{cargo}$

US fuel savings from 20% vehicle LW

Basic Equations of Vehicle Motion

The general equation for **fuel consumption (FC)** of wheeled vehicles:

\[ FC = F_m + F_{acc} + F_{aero} + F_f + F_l \]

where \( m \) denotes mass, \( acc \) is accessories, \( aero \) is aero/hydro drag, \( f \) is internal friction, and \( l \) is miscellaneous.

Mass dependence of fuel consumption:

\[ FC = FRV \times m + B \]

where **FRV is fuel reduction value**, \( m \) is vehicle mass, and \( B \) indicates non-mass-dependent factors.

\[ FRV = \frac{\Delta FC}{\Delta m} \]
FRV Modeling

- **MD and HD Trucks**
  - Simulation & dynamometer (HD) data

- **Rail**
  - Davis equation

- **Aircraft**
  - Breguet equation & PianoX

- **Ships**
  - no simple relationship between ship FC and weight (displacement).
  - our approach here is empirical, relying on data provided in a study of a set of tankers and container ships of standard design where the influence of weight on fuel consumption was estimated using a computational approach
## Fuel Reduction Values

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>( M_{gv}^a )</th>
<th>( M_{pyld} )</th>
<th>( M_{vh}^b )</th>
<th>FC</th>
<th>( F_{int} )</th>
<th>FRV</th>
<th>Drive/Duty Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadillac</td>
<td>2.04</td>
<td>0.14</td>
<td>1.90</td>
<td>8.7</td>
<td>6.38</td>
<td>0.20</td>
<td>combined cycle</td>
</tr>
<tr>
<td>Toyota Tundra</td>
<td>2.39</td>
<td>0.14</td>
<td>2.25</td>
<td>10.3</td>
<td>7.60</td>
<td>0.20</td>
<td>combined cycle</td>
</tr>
<tr>
<td>LDT-Class 2b(^1)</td>
<td>4.17</td>
<td>1.54</td>
<td>2.66</td>
<td>18.5</td>
<td>1.20</td>
<td>0.19</td>
<td>combined cycle</td>
</tr>
<tr>
<td>Class 6 Truck(^1)</td>
<td>11.79</td>
<td>7.35</td>
<td>4.47</td>
<td>41.8</td>
<td>0.57</td>
<td>0.21</td>
<td>HTUF P&amp;D Class 6</td>
</tr>
<tr>
<td>Class 8 line haul(^1)</td>
<td>36.28</td>
<td>20.59</td>
<td>15.69</td>
<td>45.1</td>
<td>0.22</td>
<td>0.062</td>
<td>HHDDT65</td>
</tr>
<tr>
<td>Transit Bus(^1)</td>
<td>18.41</td>
<td>3.72</td>
<td>13.06</td>
<td>102</td>
<td>2.75</td>
<td>0.22</td>
<td>Manhattan</td>
</tr>
<tr>
<td>Freight train(^c)</td>
<td>6,508</td>
<td>3,719</td>
<td>2,788</td>
<td>1,754</td>
<td>0.047</td>
<td>0.012</td>
<td>40 CFR 1033.530</td>
</tr>
<tr>
<td>Freight train(^d)</td>
<td>6,508</td>
<td>3,719</td>
<td>2,788</td>
<td>2,704</td>
<td>0.073</td>
<td>0.027</td>
<td>“</td>
</tr>
<tr>
<td>Aircraft - 787-8(^e)</td>
<td>173</td>
<td>23</td>
<td>115</td>
<td>583</td>
<td>2.54</td>
<td>0.30</td>
<td>ADC(^g)</td>
</tr>
<tr>
<td>Aircraft – 747-400(^f)</td>
<td>314</td>
<td>63</td>
<td>179</td>
<td>1,176</td>
<td>1.87</td>
<td>0.33</td>
<td>ADC(^g)</td>
</tr>
<tr>
<td>Oil Tanker(^2)</td>
<td>174,417</td>
<td>148,864</td>
<td>25,818</td>
<td>12,063</td>
<td>0.008</td>
<td>0.008</td>
<td>unknown</td>
</tr>
<tr>
<td>Container ship(^2)</td>
<td>110,767</td>
<td>79,184</td>
<td>31,750</td>
<td>23,910</td>
<td>0.031</td>
<td>0.019</td>
<td>unknown</td>
</tr>
</tbody>
</table>

\(^a\) This is the maximum operating mass as specified by the manufacturer often referred to gross vehicle mass, for planes this is takeoff weight, for cars and LDTs this is taken as engineering test weight;  
\(^b\) This is the vehicle mass without passengers or payload which for vehicles on tires is curb weight (mass), for planes this is operational empty weight;  
\(^c\) acceleration not included;  
\(^d\) acceleration included;  
\(^e\) Boeing 787-8, 242 passengers, no cargo, payload mass of passengers is 23.0 tonnes, 6,440 km flight, \( \Omega = 35,084 \) kms;  
\(^f\) Boeing 747-400, 350 passengers, 27.2 tonnes of cargo, 6,440 km flight, \( \Omega = 31,012 \) kms;  
\(^g\) Aircraft duty cycle;  
\(^1\) (Delorme et al. 2009);  
\(^2\) (American Bureau of Shipping 2013)

Fuel Intensities

Fuel Intensity (FI) can be defined as

\[ FI = \frac{FC}{Cargo \ mass} \]

For a Class 8 line haul truck:

- Truck cargo payload: 17 tonnes
- Fuel Consumption: 45.1 liters/100 km
- \( FI = 2.65 \ \text{liters/100 ton} \cdot \text{km} \)
Fuel Intensities

If the vehicle’s weight is reduced, two scenarios can occur

1. No cargo is added (volume limited)

\[ FI_1 = \frac{FC_{LW}}{\text{Cargo mass}} = \frac{42.9}{17} \]

\[ FI_1 = 2.53 \text{ liters/100T} \cdot \text{km} \]

4.9% FI improvement

2. More cargo is added (mass limited)

\[ FI_2 = \frac{FC_{LW}}{\text{New cargo mass}} = \frac{45.1}{20.6} \]

\[ FI_2 = 2.19 \text{ liters/100T} \cdot \text{km} \]

17.5% FI improvement
10% LW impact on Fuel Intensity

Thin-wall Cast Iron Part Example

<table>
<thead>
<tr>
<th>Problem</th>
<th>Goals and Benefits</th>
</tr>
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<tbody>
<tr>
<td>The ability to <strong>cast thin wall ductile iron (DI) castings in a high rate production environment (up to 100,000 units per year)</strong> is critical to leveraging the high stiffness and strength afforded by these materials.</td>
<td>Goal: Develop the processes required to bring <strong>thin wall, vertical green sand molded DI castings to high volume production</strong>.</td>
</tr>
<tr>
<td></td>
<td>• Benefit: Improved methods and alloys provide ability to <strong>decrease wall thicknesses by 50% and component weight by 30%-50% depending on structural loading</strong>.</td>
</tr>
</tbody>
</table>

**40% mass reduction demonstrated**

**Life cycle energy reduced by 39% for TWDCI compared to conventional cast iron differential case**

(part in a mid-sized passenger internal combustion engine vehicle (ICEV) (total mass 1369 kg) with a baseline fuel economy of 26 miles per gallon (11 km/l))

Joining & Assembly Example

Reduce warping in joining lightweight metal sheets in shipbuilding

- 6.5” out-of-plane distortion
- Flag Ship of U.S.C.G. & centerpiece of the fleet replacement program
- Most technically advanced high endurance cutter in existence
Lightweight Shipping Container Example

90% of non-bulk cargo worldwide is transported by containers, with the total world container fleet estimated at 35 million TEU (Twenty-foot Equivalent Units) (Castonguay, 2009; Theofanis and Boile, 2009)

C.A. Buchanan, M. Charara, J.L. Sullivan, G.M. Lewis, G.A. Keoleian, Lightweighting shipping containers: Life cycle impacts on multimodal freight transportation, accepted for publication in Transportation Research Part D.

Lightweighting Scenarios:

- 10% and 20% mass reduction of container panels and roof:
  - Conventional panels and roof: 1.75 tonnes
- 10% and 20% mass reduction of all steel in container:
  - Conventional steel: 3.09 tonnes
- Replacement of all Corten A steel with HTS:
  - Conventional Corten A: 3.03 tonnes
  - HTS replacement: 2.58 tonnes
- Replacement of container panels and roof with aluminum:
  - Conventional panels and roof: 1.75 tonnes
  - Al replacement: 1.12 tonnes
Assumed container lifetime of 15 years, over which it travels ~ 5.7 million km:

- Truck ~ 1 million km
- Train ~ 556,000 km  \(\text{Within the US}\)
- Ship ~ 4.2 million km  \(\text{To and from the US}\)
Fuel saved over one shipping container’s lifetime (~ 5 million km).

C.A. Buchanan, M. Charara, J.L. Sullivan, G.M. Lewis, G.A. Keoleian, Lightweighting shipping containers: Life cycle impacts on multimodal freight transportation, accepted for publication in Transportation Research Part D.
Fleet-wide results show significant savings in fuel and reduction in energy demand.

- **U.S. fuel savings over 15 years are 5.4 – 6.9 billion liters.**

Over 15 year U.S. multimodal container lifetime, lightweighting all steel 20% leads to a reduction in energy consumption of:

- 0.20 – 0.26 EJ in the U.S. (truck & train)
- 2.7 – 3.6 EJ globally (ship)

For reference, 2015 U.S. energy consumption was ~100 EJ.
Conclusions

- Greatest opportunities for fuel savings from LW:
  LDT1 > Cars > HDT > Air > MDT > Rail > Ship

- Cost driver greatest with Aircraft $/kg LW

- Distinguish FC vs Fuel Intensity benefits
  - Largest reductions in FI for Aircraft

- Enabling manufacturing technologies critical factor
  influencing material trends
Conclusions

• Evaluate full life cycle to elucidate tradeoffs from LW

• As powertrains get more efficient, LW becomes a less effective fuel saving strategy

• LW principles to guide design and implementation under development through LIFT
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